Fermi National Accelerator Laboratory

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CP Violation Experiment at Fermilab *

The E-731 Collaboration

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CP VIOLATION EXPERIMENT AT FERMILAB

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The E731 experiment at Fermilab has searched for "direct" CP violation in $K^0 \to \pi\pi$, which is parametrized by ε'/ε. For the first time, in 20% of the data set, all four modes of the $K_{L,S} \to \pi^+\pi^-(\pi^0\pi^0)$ were collected simultaneously, providing a great check on the systematic uncertainty. The result is $\mathrm{Re}(\varepsilon'/\varepsilon) = -0.0004 \pm 0.0014(\mathrm{stat}) \pm 0.0006(\mathrm{syst})$, which provides no evidence for "direct" CP violation.

The CPT symmetry has also been tested by measuring the phase difference $\Delta\phi = \phi_{00} - \phi_{+-}$ between the two CP violating parameters η_{00} and η_{+-}. We find $\Delta\phi = -0.3° \pm 2.4°(\mathrm{stat}) \pm 1.2°(\mathrm{syst})$. Using this together with the world average ϕ_{+-}, we find that the phase of the K^0-$\bar{K}^0$ mixing parameter ε is $44.5° \pm 1.5°$. Both of these results agree well with the predictions of CPT symmetry.

INTRODUCTION

CP violation was first observed[1] in the $\pi^+\pi^-$ decay of the long-lived neutral kaon (K_L) about 26 years ago; this and many subsequent mea-

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* E731 is a collaboration of University of Chicago, Elmhurst College, Fermilab, Princeton University and Centre d'Etudes Nucleaires de Saclay.

surements point to a very small asymmetry in the mixing of K^0 and $\bar{K}^0$, parametrized by $|\varepsilon| \approx 2.3 \times 10^{-3}$. The six-quark model[2] of Cabbibo, Kobayashi and Maskawa (CKM) provides the most natural way of incorporating CP violation into the weak interaction, especially since the discovery[3] of the bottom quark, this has provided increased motivation for further studies. Until very recently, the only observed CP-nonconserving effects were consistent with asymmetric K^0-$\bar{K}^0$ mixing. This is a second-order effect in the CKM framework, but could also signal a new $\Delta S = 2$ interaction (e.g., superweak[4]). The CKM mechanism has one consequence, a second manifestation of first-order ("direct") CP nonconservation in the $K^0(\bar{K}^0) \rightarrow 2\pi$ decay itself, parametrized by ε'/ε, is also expected. Search for such effect in the predicted range provide an important test of the model. Recently, the NA31 group at CERN has reported[5] a 3σ non-zero effect, while theoretical prediction when includes the Z-penguin diagram shows[6] a strong top quark mass dependence and a heavy top quark ($m_t > 200$ GeV/c^2) will push ε'/ε very close to zero.

The K^0 and $\bar{K}^0$ are the strong interaction eigenstates during the production, because the strong interaction conserves strangeness. The kaon decay through the weak interaction allows $\Delta S = \pm 1$ transitions. They also mix with each other through intermediate $S = 0$ states (e.g. 2π and 3π). Taking into account the small CP violation (ε) in the K^0-$\bar{K}^0$ mixing, the vacuum eigenstates are: $K_{S,L} = [\,(1+\varepsilon)K^0 \pm (1-\varepsilon)\bar{K}^0\,] \,/\, \sqrt{2(1+\varepsilon^2)}$, where the plus sign is for K_S and the minus sign for K_L. The parameter ε introduces a small CP-even impurity into the long-lived state (K_L), allowing it to decay into the 2π final states. The two complex parameters η_{+-} and η_{00} are defined as the ratios of K_L and K_S decay amplitudes into $\pi^+\pi^-$ and $\pi^0\pi^0$, where $\eta \equiv amp(K_L \rightarrow \pi\pi) \,/\, amp(K_S \rightarrow \pi\pi)$. Neglecting a small ($\approx 5\%$) violation of the $\Delta I = 1/2$ rule, we have: $\eta_{+-} \equiv |\eta_{+-}|\, e^{i\phi_{+-}} = \varepsilon + \varepsilon'$ and $\eta_{00} \equiv |\eta_{00}|\, e^{i\phi_{00}} = \varepsilon - 2\varepsilon'$. Here, ε' parametrizes any additional CP violation arising directly from the 2π decay amplitudes, so called "direct" CP violation. The experiment seeks to isolate such an effect by measuring the double ratio R of the decay rates of K_L and K_S to charged and neutral pions:

$$R = \frac{|\eta_{+-}|^2}{|\eta_{00}|^2} = \frac{\Gamma(K_L \rightarrow \pi^+\pi^-)/\Gamma(K_S \rightarrow \pi^+\pi^-)}{\Gamma(K_L \rightarrow \pi^0\pi^0)/\Gamma(K_S \rightarrow \pi^0\pi^0)} \cong 1 + 6\,\mathrm{Re}(\varepsilon'/\varepsilon).$$

The expected value of $\mathrm{Re}(\varepsilon'/\varepsilon)$ is below 10^{-2}, this translates to a small deviation (less than a few percent) of R from unity.

CPT symmetry is expected to be exact in local quantum field theories (CPT theorem[7]), and as a consequence the masses and lifetimes of particle-antiparticle pairs should be equal. Direct measurements of mass and lifetime differences ($\delta M/M$ and $\delta\Gamma/\Gamma$) have achieved sensitivity at the 10^{-7} level.[8] Since the mass difference between K^0 and $\bar{K}^0$ is limited by the difference (Δm) between K_L and K_S, and with $\Delta m/m_K = 7 \times 10^{-15}$, the neutral kaons are expected to provide the most sensitive tests on CPT symmetry. Reviews of the neutral kaon system together with the CP and CPT phenomenology can be found in the literature.[9,10] The issue of CPT symmetry for neutral kaons is connected to the phases of ε and ε', which are related to the (measurable) phases of η_{+-} and η_{00}. The expression for ε is:

$$\varepsilon = \frac{1}{2}\frac{\langle\bar{K}^0|H|K^0\rangle - \langle K^0|H|\bar{K}^0\rangle}{(m_L - m_S) + i(\Gamma_S - \Gamma_L)/2},$$

here, $H = M - i\Gamma/2$ is the Hamiltonian of the K^0-$\bar{K}^0$ system, and m_L, m_S, Γ_L and Γ_S are the K_L and K_S masses and decay rates. The mass and decay matrices (M and Γ) are both hermitian, making the numerator equal to $2i\mathrm{Im}M_{12} + \mathrm{Im}\Gamma_{12}$. Using results from 3π and semileptonic decay modes, one can show[9] that the contribution to ε from the decay matrix is very small compared to the contribution from the mass matrix. Consequently, the phase of ε (measured as $2\phi_{+-}/3 + \phi_{00}/3$) should be within a few degrees to the natural angle $\phi_\varepsilon = \arg(\Gamma_S/2 + i\Delta m) = 43.7° \pm 0.2°$. Another prediction of CPT symmetry is obtained by considering the phase of ε'. This parameter is written as

$$\varepsilon' = \frac{i}{\sqrt{2}}\frac{\mathrm{Im}A_2}{\mathrm{Re}A_0}e^{i(\delta_2-\delta_1)},$$

where A_I is the decay amplitude of K^0 into 2π final state of isospin I with a phase shift δ_I from final state interactions. Using the experimental value[11] $\delta_2 - \delta_0 = -45° \pm 10°$ and the smallness of $\mathrm{Re}(\varepsilon'/\varepsilon)$, it can be seen that the difference between ϕ_{+-} and ϕ_{00} should be much less than one de-

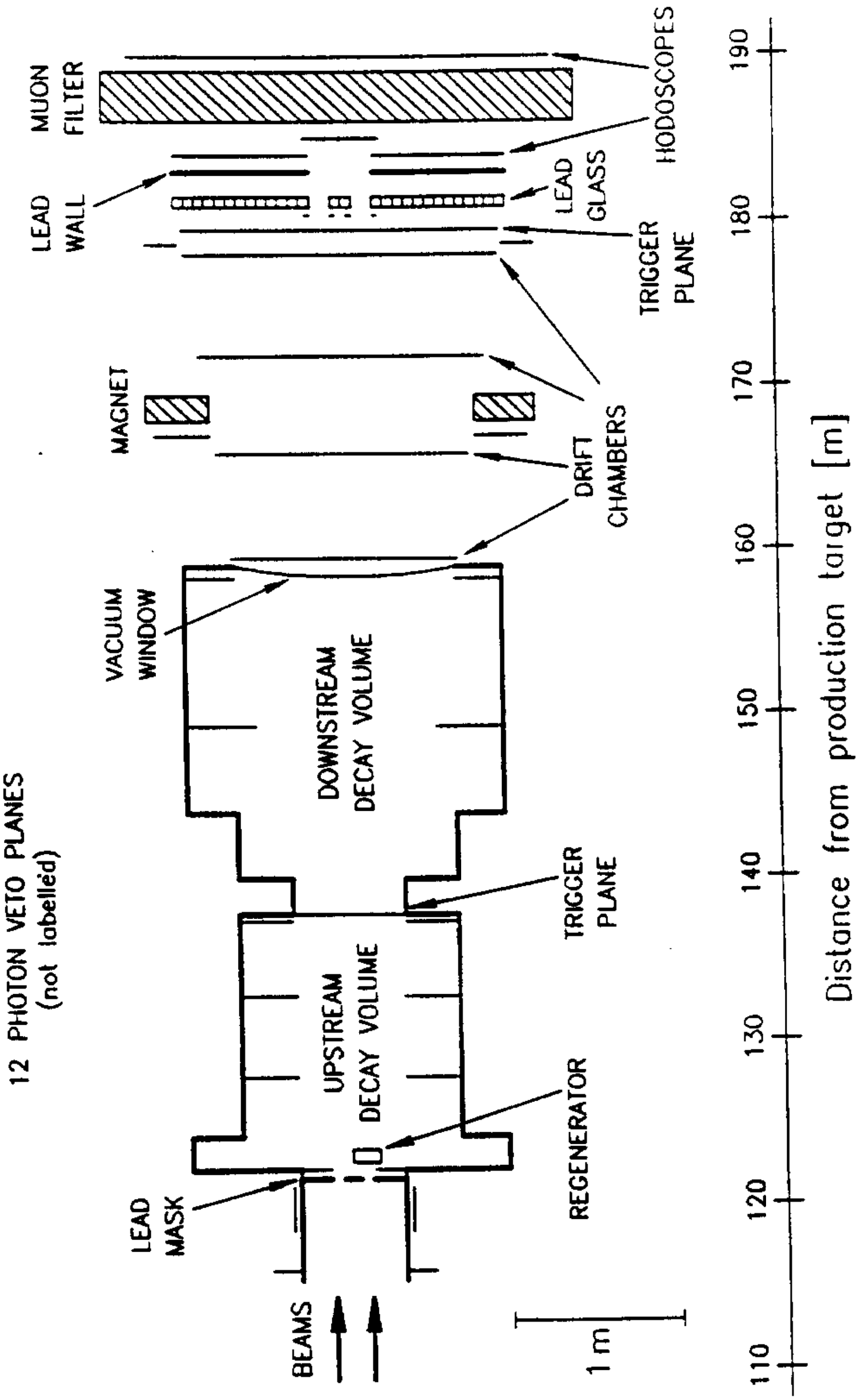


Fig. 1: The E731 detector.

gree. However, the world average values[12] $\phi_{+-} = 44.6° \pm 1.2°$ and $\phi_{00} = 54° \pm 5°$ violate both CPT predictions at about two standard deviations.

EXPERIMENT E731

Because of the smallness of Re(ε'/ε), it is important to minimize systematic uncertainty in the collection and analysis of the four decay modes. In our experiment, the K_S are provided by coherent regeneration, ensuring an angular divergence identical to that of the K_L, and very similar momentum spectra for $\pi\pi$ events. Decays of K_S and K_L to a given final state (charged or neutral) are collected at the same time by means of side-by-side K_L and K_S beams, so electronic drifts, accelerator instabilities, and phototube gain shifts affecting them are virtually identical. Furthermore, the regenerator alternates between the two beams, rendering the effect of asymmetries in the beams or the detector response negligible.

Neutral kaons were produced by 800 GeV protons incident at 5 mrad on a beryllium target, after which collimators and sweeping magnets produced two neutral kaon beams. Average kaon energy was about 70 GeV. The E731 detector is shown in Fig. 1. A boron carbide (B_4C) regenerator, instrumented to detect inelastic regeneration, was placed in one of the beams about 123 m downstream of target to create K_S component, so called "regenerated" beam. The other "vacuum" beam is essentially a pure K_L beam. The regeneration of K_S comes about because of the cross sections difference between the K^0 and $\bar{K}^0$ in ordinary matter. An incident K_L, which is one particular linear combination of K^0 and $\bar{K}^0$, will turn into a different linear combination, thus picking up a K_S component. Only the coherently scattered kaons (in the forward direction) have the same beam profile and angular divergence as the original K_L beam. By instrumenting the regenerator with scintillators and phototubes, we rejected a good fraction of the inelastically scattered kaons at trigger level. The remaining small incoherently scattered kaons (diffractive and inelastic) were subtracted using the kaon transverse momentum (p_t^2) or some other similar variable.

The end of upstream decay volume, located at 137.8 m from target, was defined by a pair of thin scintillator planes, which were used in the

$\pi^+\pi^-$ trigger together with another pair of scintillator planes located after the spectrometer at 179.5 m. The two charged tracks from the $\pi^+\pi^-$ events were reconstructed using the four drift chambers and the track momenta determined by the analysis magnet. Each drift chamber had two x and two y planes (offset by half wire spacing) with a resolution of about 110 μm per plane. The $\pi\mu\nu$ decays were rejected with the muon hodoscope behind, 3 m of iron shielding, the muon filter. Thus $\pi e\nu$, $\pi^+\pi^-\pi^0$ as well as $\pi^+\pi^-$ decays were accepted.

The $\pi^0\pi^0$ decays resulted in four photons which shower in the lead glass calorimeter, located 181 m from target, with an energy resolution of 2.5%(1.5%) + $5\%/\sqrt{E}$ (E in GeV) for photons (electrons). There were 804 lead glass blocks stacked in a roughly circular array (with two beam holes), and the number of photon clusters was determined by a trigger processor. The trigger required four or six isolated clusters (with each cluster's energy greater than 1 GeV) and a total energy of about 28 GeV, accepting $\pi^0\pi^0\pi^0$ as well as $\pi^0\pi^0$ decays. The main background of $\pi^0\pi^0$ comes from $3\pi^0$ decays where two photons escape the lead glass or emerge with other photons. To suppress this background, eleven planes of photon veto counters were employed to intercept photons leaving the detector. The calorimeter was followed by a hadron veto consisting of a lead wall and a scintillator hodoscope.

The data taking took place between July 1987 and February 1988, and the results presented here, have been published[13,14] recently, are based on 20% of the total sample. During this particular data set, both $\pi^+\pi^-$ (prescaled by 8) and $\pi^0\pi^0$ decays were collected simultaneously, providing a very good control of systematics.

At downstream of regenerator, as a function of proper time t from the regenerator, the $\pi\pi$ decay rates in the vacuum and regenerated beams are proportional to $|\eta|^2$ and $|\rho\ \exp(-t/2\tau_S+i\Delta m\ t) + \eta|^2$, respectively; where ρ is the coherent regeneration amplitude, τ_S is the K_S lifetime, Δm is the K_L–K_S mass difference, and η is the appropriate ratio of K_L-to-K_S decay amplitudes. Because $|\rho| >> |\eta|$, the ratio of the total number of regenerated to vacuum charged (neutral) decays R_{+-} (R_{00}) is proportional to $|\rho/\eta_{+-(00)}|^2$. Thus, $R \approx R_{+-}/R_{00}$.

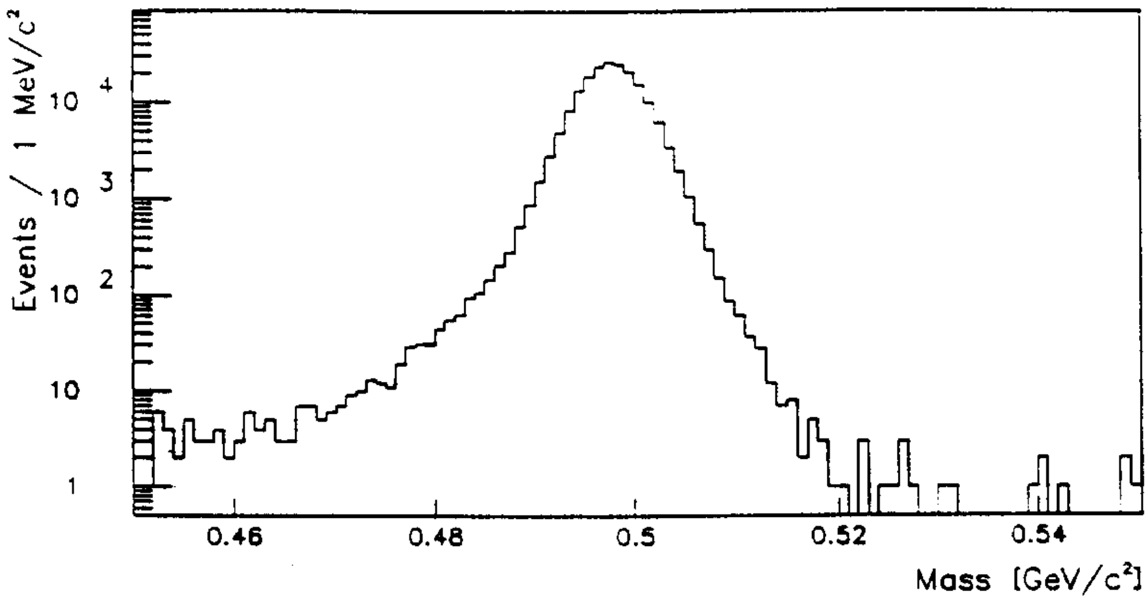


Fig. 2: $\pi^+\pi^-$ invariant mass in the regenerated beam.

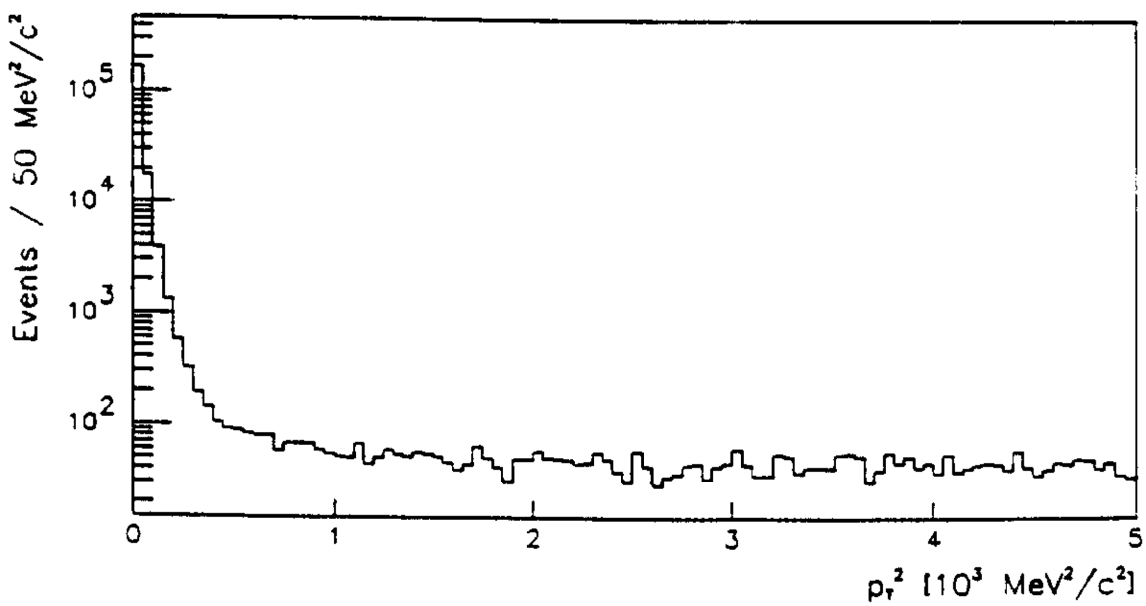


Fig. 3: Transverse momentum squared in the regenerated beam.

ANALYSIS

The $\pi^+\pi^-$ invariant mass was calculated assuming the charged pion mass for each track. Projecting the kaon back from the decay vertex to the regenerator plane, the transverse momentum was determined with respect to a line from the target. The $\pi e\nu$ decays were suppressed by using the measured energy in the lead glass calorimeter to calculate E/p for the tracks. Figure 2 shows the invariant mass of K_S in the regenerated beam after all other cuts. with a resolution of about 3.5 MeV/c^2. The signal region is defined as 484 to 512 MeV/c^2. The low-side tail is due to radiative $\pi^+\pi^-\gamma$. The transversed momentum squared (p_t^2) is plotted in Figure 3 for kaons with good mass in the regenerated beam, where the incoherent background is fitted to a functional form with exponential terms representing the diffractive and inelastic contributions. With a cut of 250 (MeV/c)^2, the background under the coherent peak is found to be (0.13 ± 0.01)%. The corresponding background in the vacuum beam is (0.32 ± 0.06)%, which is due to the residual $\pi e\nu$ decays.

The decay vertex for $K_{L,S} \to \pi^0\pi^0$ decays was found by pairing the photons using the known π^0 mass as a constraint. The $\pi^0\pi^0$ invariant mass is shown in Fig. 4a for K_L decays, differentiated from K_S decays by means of the center of energy of the four photons in the calorimeter. The signal region is between 480 and 516 MeV/c^2. The residual background from $K_L \to \pi^0\pi^0\pi^0$ decays was (0.37 ± 0.07)%, and was well reproduced by a Monte Carlo simulation. The invariant mass for K_S decays is shown in Fig. 4b. For neutral decays, only the center of energy at the calorimeter was available to identify incoherently regenerated K_S, which scattered into both vacuum and regenerated beams. Their contributions were accurately predicted from the p_t^2 distribution for simultaneously observed $\pi^+\pi^-$ decays. Figure 5a (5b) shows the size and shape of this prediction agree very well with the observed event density distribution in equal-area concentric rings around the K_L (K_S) beam. The background under the coherent beam was found to be [4.70 ± 0.14(syst)]% for K_L and [2.56 ± 0.07(syst)]% for K_S.

Acceptance corrections, which is necessary because of the difference in K_S and K_L vertex distributions, were made using a detailed Monte Carlo simulation of the beam and detector. The nonlinearity and non-

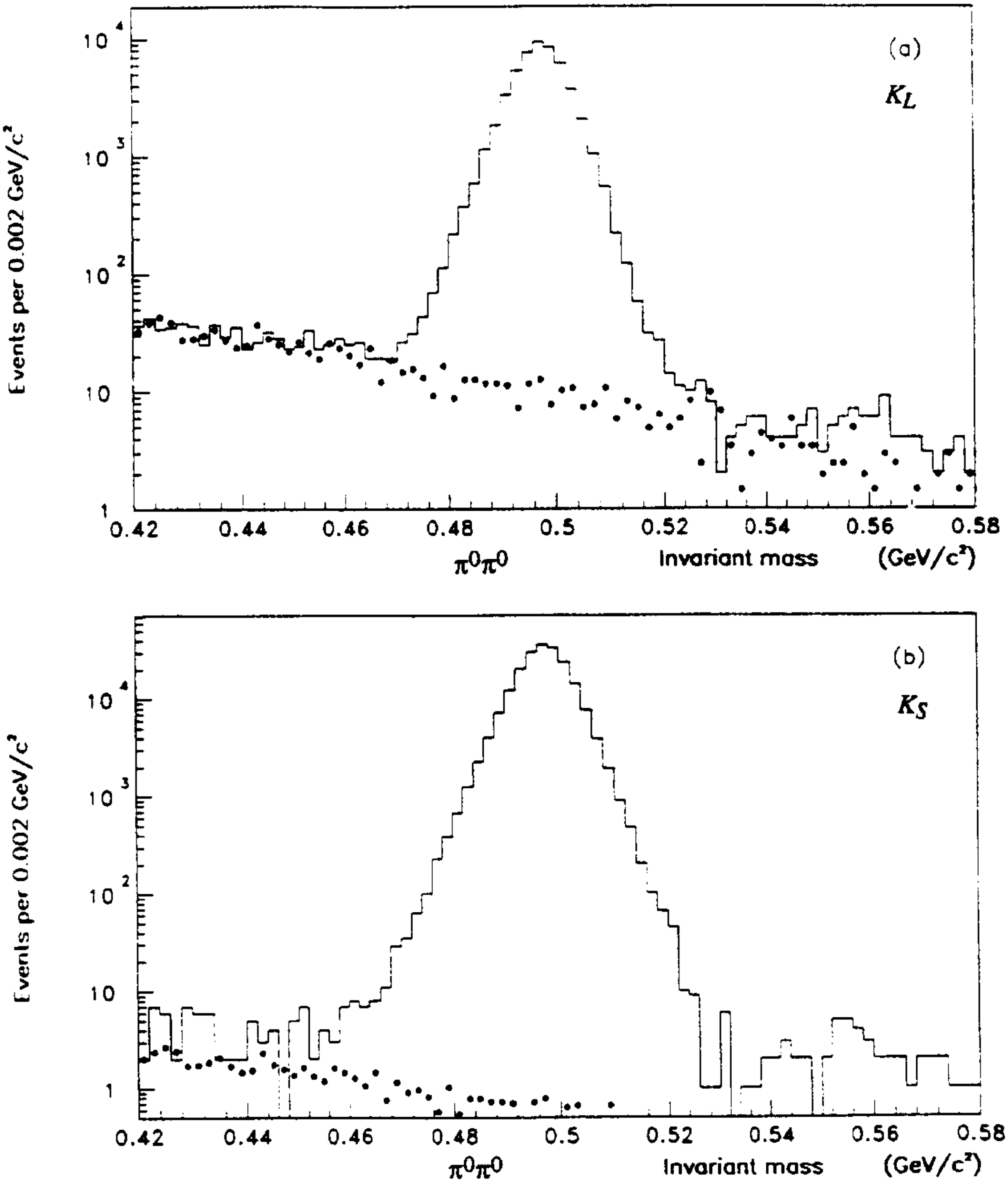
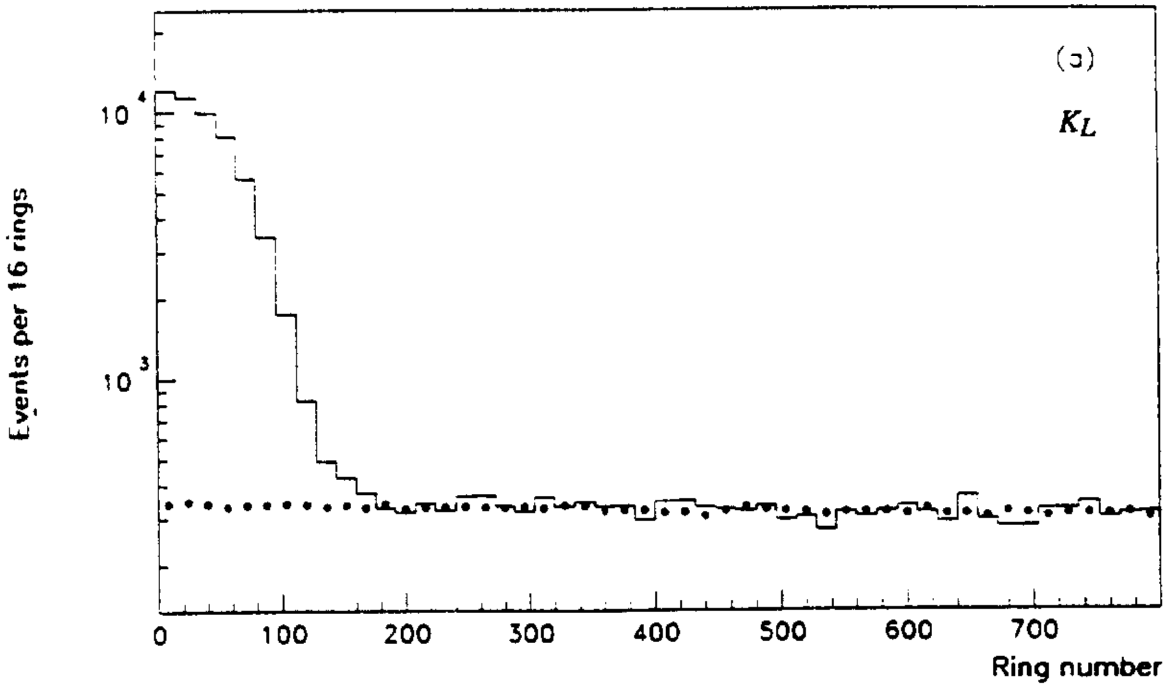


Fig. 4: Neutral mode $\pi^0\pi^0$ invariant mass for (a) K_L beam, (b) K_S beam; where the solid circles show the $3\pi^0$ background simulation predicted by Monte Carlo.



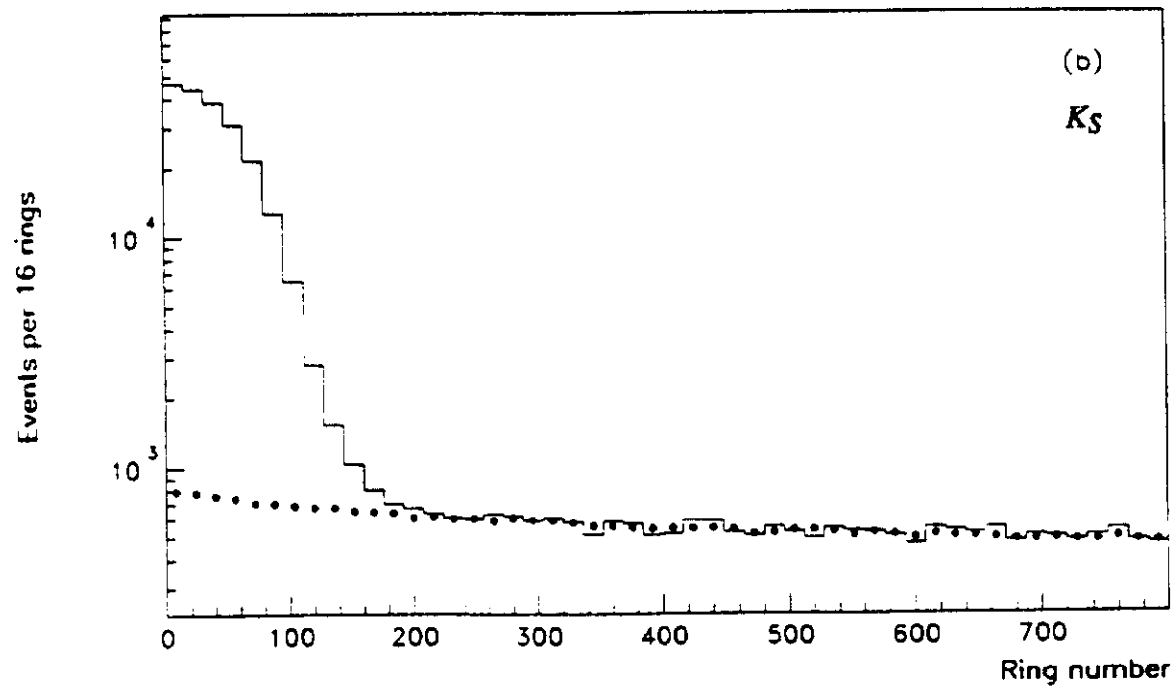


Fig. 5: Event density in equal-area concentric rings around the (a) K_L beam, (b) K_S beam for $\pi^0\pi^0$ events. The solid circles show the expected size and shape of incoherent background from the regenerator as determined from $\pi^+\pi^-$.

Gaussian response of the lead glass to photons, affecting the vertex reconstruction in neutral decays, were reproduced with no free parameters, using results from EGS simulations together with the effective attenuation length of Cherenkov light in each block. The restriction that the *same* detector and beam parameters be used in the simulation of all four modes, since all were collected simultaneously, provided a powerful check of the Monte Carlo simulation as a whole. The $K_L \to \pi^+\pi^-$ decay-vertex distribution is well reproduced by the Monte Carlo simulation, as shown in Fig. 6. The agreement is equally good for the other decays.

The final sample included kaons with energy between 40 and 150 GeV decaying in the region from 120 to 137 m from the target. The raw number of events passing all cuts and the background and acceptance corrections are given in Table I with the ratio of R_{+-}/R_{00} at each stage. The acceptance was similar for K_S and K_L: It varied slowly with decay vertex, the mean of which differed for K_S and K_L decays by less than 1.5 m. The total change in the double ratio from raw data to final acceptance-corrected samples is 7%. The final double ratio indicates a small value of Re(ε'/ε). Fig. 7 shows the stability of the ratio K_S/K_L for neutral and charged modes in seven mini-periods, while the beam intensity had varied more than 40%.

	Neutral	Charged	R_{+-}/R_{00}
Raw events			
K_L	52226	43357	
K_S	201332	178803	1.0698
Background fractions			
K_L	0.0507	0.0032	
K_S	0.0256	0.0013	1.0442
Acceptance			
K_L	0.1884	0.5041	
K_S	0.1813	0.5064	1.0003

Table I. Event totals and corrections.

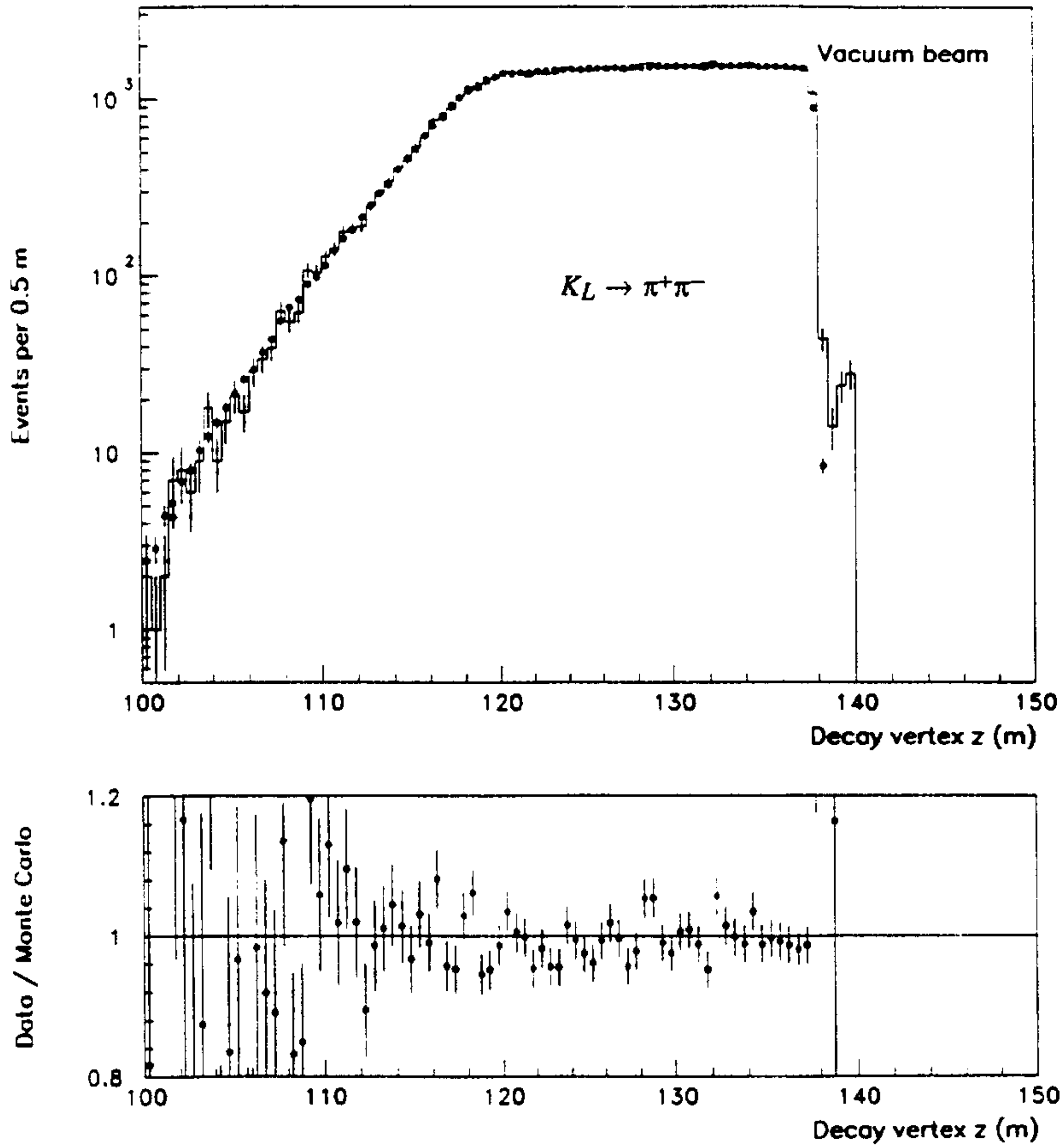


Fig. 6: Decay vertex distribution for $K_L \to \pi^+\pi^-$ events. The histogram is data and the solid circles are from a Monte Carlo simulation. Lower plot is the ratio of data divided by Monte Carlo.

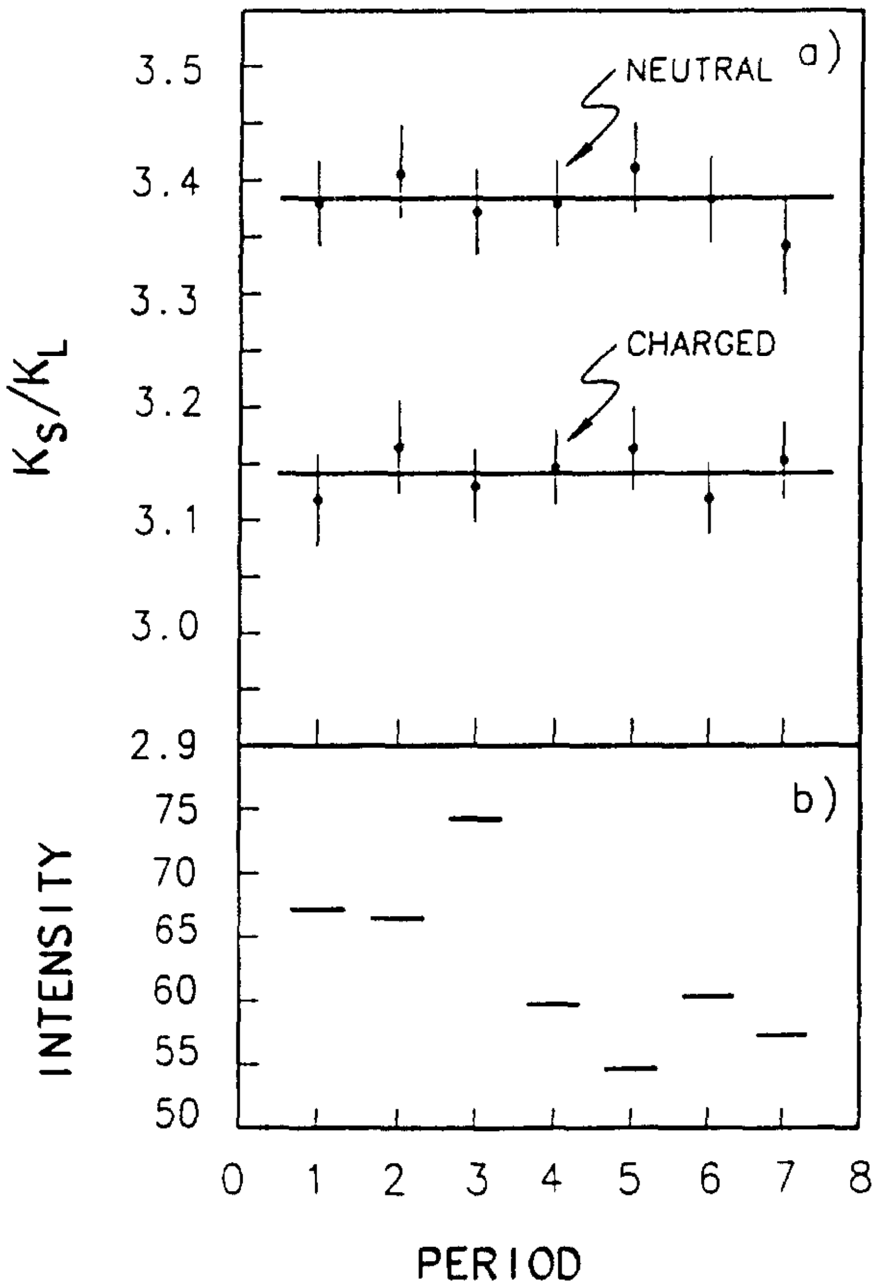


Fig. 7: (a) Ratio of reconstructed K_S / K_L for neutral and charged mode vs mini-periods, (b) The beam intensity on target vs mini-periods.

EXTRACTION OF Re(ε'/ε) AND $\Delta\phi$

To extract Re(ε'/ε), we fit R_{+-} and R_{00} for $|\rho/\eta|$ in the two modes in 10 GeV/c bins of kaon momentum. The momentum dependence, common to the neutral and charged modes, is expected to obey a power law,[15] while a magnitude difference is proportional to Re(ε'/ε). Figure 8a and 8b shows the fitted power law dependence for $|\rho/\eta|$. The best-fit power for the charged (neutral) mode was -0.602 ± 0.010 (-0.605 ± 0.010) with $\chi^2 =$ 11.5 (10.7) for 9 degrees of freedom. The two are consistent with each other and with previous determinations.[16] The combined fit yielded Re(ε'/ε) $= -0.0004 \pm 0.0014$(stat).

Systematic errors were associated with background subtractions, detector and beam variations with time, accidental activity in the detector, energy calibration and resolution, and acceptance.

Uncertainty in the backgrounds is dominated by those in the incoherent contributions to neutral decays, which are expected to partially cancel in R_{00}. As a conservative estimate of the total uncertainty on the double ratio all background errors are added in quadrature, yielding a total of 0.18%. All decays to a common final states were analyzed together, this and the use of loose cuts (the reconstruction efficiency was more than 90%) reduced sensitivity to time variations. Therefore R_{+-} and R_{00} were stable throughout the run, even though the intensity, targeting, and detector efficiencies varied.

Accidental activity, concentrated near the vacuum beam, could have changed the relative K_L and K_S efficiencies. Accidental events, collected with $\pi\pi$ data at a rate proportional to the instantaneous beam intensity, contained a photon cluster 2.7% of the time and an average of 8.5 chamber hits. When overlaid on the $\pi\pi$ Monte Carlo events they correctly reproduced the small intensity dependence of our selection criteria. However, no bias between K_L and K_S was seen within the statistical error of the simulation (0.07%) for either mode.

The energy scale accuracy for the charged was determined sufficiently using the known K^0 and Λ masses. For the neutral mode, the overall scale was adjusted ($\approx$0.5%) using the sharp edge in the K_S decay vertex at the regenerator, leaving a residual uncertainty of 0.1%. By

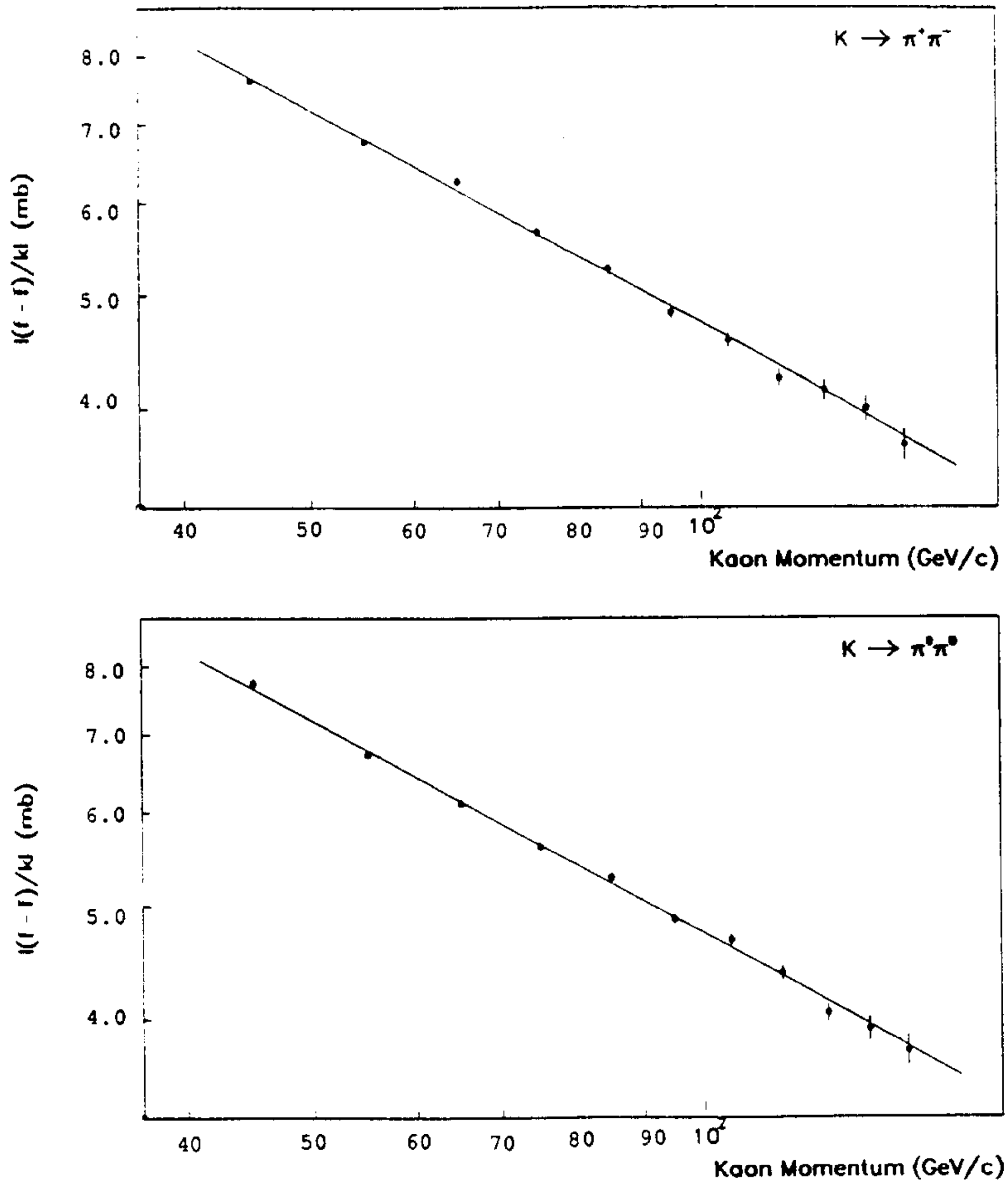


Fig. 8: The fit of $|\rho/\eta|$ vs kaon momentum for (a) $\pi^+\pi^-$ mode and (b) $\pi^0\pi^0$ mode data.

choosing the fiducial decay region, this resulted in only 0.03% uncertainty in R_{00}. The uncertainty in energy resolution led to an 0.2% uncertainty in R_{00}.

Acceptances were extensively studied using 10^7 $\pi e\nu$ and 6×10^6 $\pi^0\pi^0\pi^0$ decays taken with the $\pi\pi$ events. The agreement in vertex, momentum and other distributions with Monte Carlo simulation over the chosen fiducial region was excellent. Also, when Re(ε'/ε) was extracted using small vertex bins (eliminating the need for acceptance corrections), a consistent result was obtained. In the same analysis, we fit for τ_S and Δm. Separate neutral and charged fits were consistent and the combined results were τ_S = [0.8902 ± 0.0021(stat)] × 10^{-10} sec and Δm = [0.534 ± 0.009(stat)] × 10^{10} $\hbar$ sec^{-1}, in agreement with the accepted values.[12] These studies, together with the stability of R_{+-} and R_{00} when selection criteria, beam profiles and detector apertures and efficiencies were varied in the Monte Carlo simulation, led us to assign 0.25% systematic uncertainty due to acceptance.

Combining these uncertainties in quadrature, the total systematic error on the double ratio is then 0.38%. The final result is

$$\mathrm{Re}(\varepsilon'/\varepsilon) = -0.0004 \pm 0.0014(\mathrm{stat}) \pm 0.0006(\mathrm{syst}).$$

The result is consistent with the superweak model; it does not confirm recent evidence[5] for direct CP violation from NA31 at CERN. The CKM standard model may also account for such a small value of Re(ε'/ε) with a heavy top quark .

To extract the phases in the regenerated beam, we have extended the analysis of neutral mode decay region to 147 m from the target to have more sensitivities. This has increased the background contributions in neutral mode slightly. The background under the coherent peak was found to be 2.7% in the regenerated beam and 2.8% in the vacuum beam. The $3\pi^0$ background in the vacuum beam has rose to 0.99% due to nuclear interactions in the trigger hodoscope at 137.8 m. The vacuum beam served as to normalize the incident kaon flux on the regenerator. The 2π decay rates as a function of proper time t (measured from the regenerator) are given by $|\eta|^2 e^{-t/\tau_L}$ for the vacuum beam and e^{-X} $[|\rho|^2 e^{-t/\tau_S} + |\eta|^2 e^{-}$

$^{t/\tau_L} + 2|\rho|\,|\eta|\, e^{-t/2\tau_S}\ \cos(\Delta m\, t + \phi_\rho - \ \phi_\eta\ )]$ for the regenerated beam. Given that the regenerator alternates, the incident kaon momentum spectrum is the same for both beams, except that the flux in the regenerated beam is reduced by absorption, which is accounted for by the factor e^{-X}. This factor is measured with sufficient precision by comparing the number of $K_L \rightarrow \pi^+\pi^-\pi^0$ and $K_L \rightarrow \pi^0\pi^0\pi^0$ decays in the two beams.

By fitting the data and Mont Carlo distributions against each other, the phases $\phi_{+-}$and ϕ_{00} (denoted ϕ_η above) are extracted from the interference pattern in the regenerated beam. The overall normalization is provided by the event totals in the vacuum beam. The phase ϕ_ρ is fixed by the analyticity condition $\arg[(f-\bar{f})\,/\,k] = -(2-\alpha)\pi\,/\,2$, where $(f-\bar{f})\,/\,k$ is the difference between the K^0 and $\bar{K}^0$ forward scattering amplitudes related to the regeneration amplitude ρ, which has a power law dependence on the kaon momentum, *i.e.*, $|\rho| \propto p_K{}^{-\alpha}$.

The result of the fit, is $\phi_{+-}= 47.7° \pm 2.0°$(stat) and $\phi_{00} = 47.4° \pm 1.4°$(stat), with $\chi^2 = 316$ for 340 degrees of freedom. Thus $\Delta\phi = \phi_{00} - \phi_{+-} = -0.3° \pm 2.4°$(stat). Figure 9 and 10 show the extracted cosine factor from the interference term together with the best fit. The available proper time interval is shorter for the $\pi^+\pi^-$ decays, due to the trigger plane at 137.8 m. (Note: One K_S lifetime is about 27 degrees.) The results for ϕ_{+-} and ϕ_{00} depend directly on the value of ϕ_ρ, but the difference $\Delta\phi = \phi_{00} - \phi_{+-}$ is insensitive to ϕ_ρ. By varying the fixed parameters Δm and τ_S one standard deviation around their accepted values, the uncertainty in ϕ_{+-} (ϕ_{00}) is found to be 0.4° (0.5°) for Δm and 0.8° (0.6°) for τ_S. Similarly, the uncertainty in the factor e^{-X} leads to a systematic error of 0.4° (0.3°). In all three cases, the effect on the difference $\Delta\phi$ is negligible.

The systematic errors on $\Delta\phi$ come from various sources. The uncertainty in the acceptance gave an error in $\Delta\phi$ of 0.9°. the uncertainty in the absolute energy calibration (0.1%) resulted an error in $\Delta\phi$ of 0.6°. The background subtraction contributed an error of 0.3°. The combined systematic error on $\Delta\phi$ is thus 1.2°. The final result is

$$\Delta\phi = \phi_{00} - \phi_{+-} = -0.3° \pm 2.4°(\text{stat}) \pm 1.2°(\text{syst}).$$

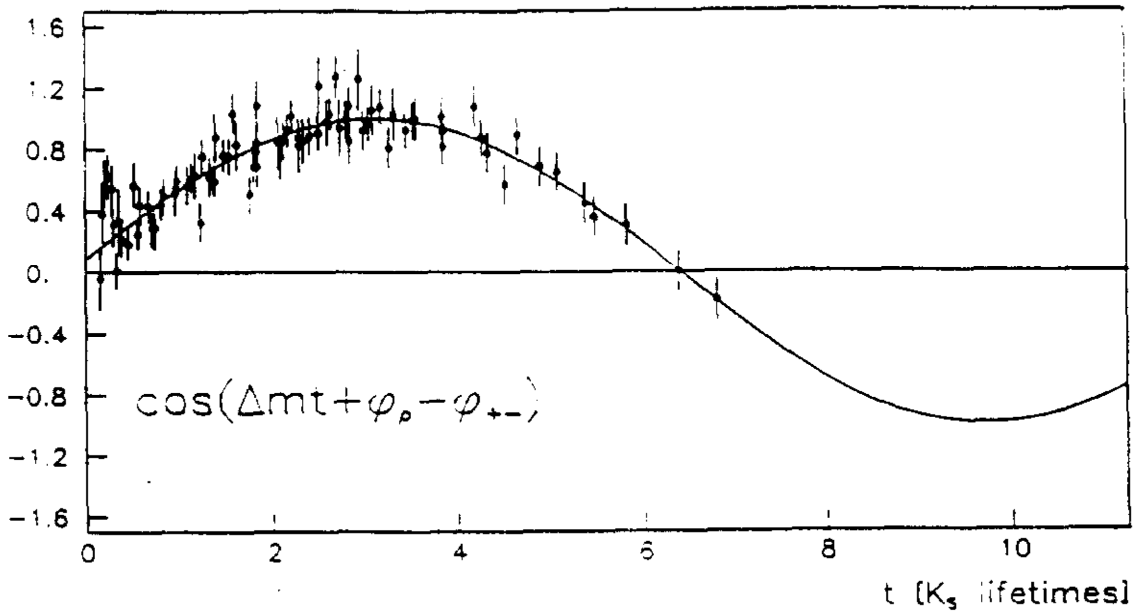


Fig. 9: Extracted cosine term from the $\pi^+\pi^-$ decay rate.

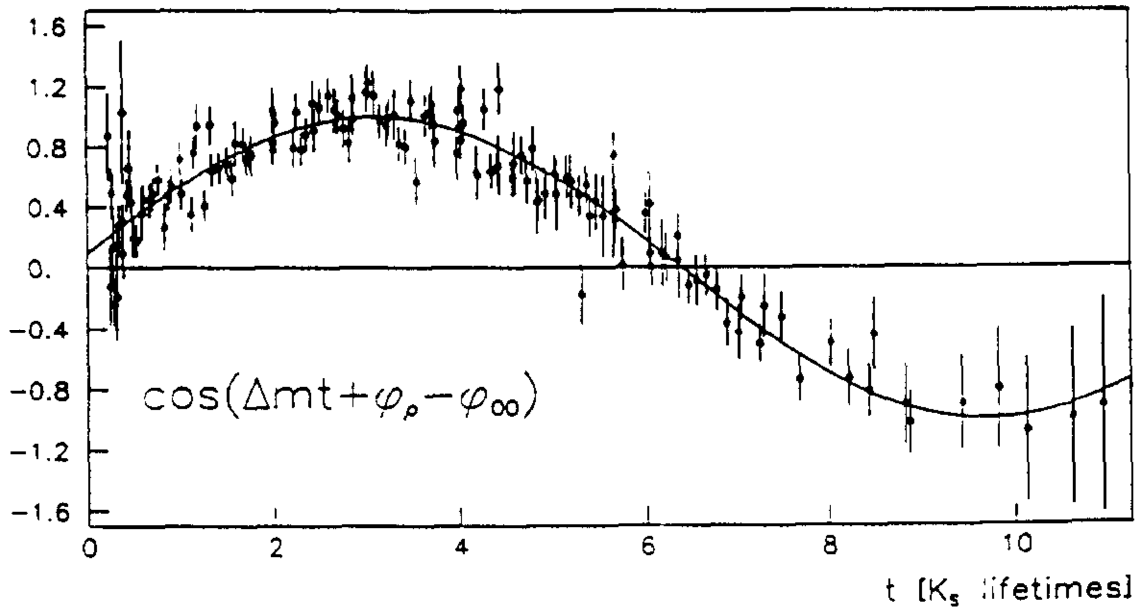


Fig. 10: Extracted cosine term from the $\pi^0\pi^0$ decay rate.

Together with the world average value of ϕ_{+-}, we find that $\phi_\varepsilon = 2\phi_{+-}/3 + \phi_{00}/3 = 44.5° \pm 1.5°$. Both results agree with the predictions of CPT symmetry. A recent measurement[17] by NA31 group (a dedicated run separated from their ε'/ε measurement) has also found that $\Delta\phi$ is consistent with zero.

If there were any CPT violation in the K^0-$\bar{K}^0$ mixing, it would be parametrized by

$$\Delta = \frac{1}{2}\,\frac{\langle \bar{K}^0 |\, H\, | \bar{K}^0 \rangle - \langle K^0 |\, H\, | K^0 \rangle}{(m_L - m_S) + i\,(\Gamma_S - \Gamma_L)/\,2} \,,$$

and any violation in the 2π decay amplitudes by $a = (A_0 - \bar{A}_0)\,/\,(A_0 + \bar{A}_0)$. The K_L and K_S amplitude ratios would then be given by $\eta_{+-} = \varepsilon - \Delta + a + \varepsilon'$ and $\eta_{00} = \varepsilon - \Delta + a - 2\varepsilon'$. The expression contains the K^0-$\bar{K}^0$ mass and lifetime differences in its numerator. Together with limits from 3π and semileptonic decay modes, our results set a limit of about 4×10^{-18} for $\delta M/M$ and about 2×10^{-4} for $\delta\Gamma/\Gamma$.

CONCLUSIONS

We have analyzed 20% of full data sample, in which all four modes of neutral kaon 2π decays were measured simultaneously. Our results on $\mathrm{Re}(\varepsilon'/\varepsilon)$ and $\Delta\phi$ are both consistent with zero. We have not yet seen the direct CP violation at the level of 10^{-3} in $\mathrm{Re}(\varepsilon'/\varepsilon)$, this result is about two standard deviations away from the NA31's measurement. Our $\Delta\phi$ measurement strongly supports the CPT symmetry and ruled out the earlier two standard deviation effect.[12] More data has now been analyzed, we expect our final precision on $\mathrm{Re}(\varepsilon'/\varepsilon)$ is better than $\pm$ 0.0006(stat) $\pm$ 0.0006(syst).

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